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Implementation of Structures in the CMS: Part III, Culvert

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PURPOSE: This Coastal and Hydraulics Engineering Technical Note (CHETN) describes the mathematical formulation and numerical implementation of a culvert in the Coastal Modeling System (CMS) operated through the Surface-water Modeling System (SMS). A coastal application is provided to illustrate the implementation procedure at Poplar Island, MD.

INTRODUCTION: Culverts are a common coastal engineering structure typically used in coastal wetlands to control waste and storm water discharges, act as salinity barriers, optimally distribute freshwater, and manage sediment transport (Figure 1). In coastal applications, the culverts often connect open water bodies of similar water surface elevation to enhance flushing or conduct flow through levees or causeways. Since culverts are a significant component of hydrodynamic and sediment transport controls in the coastal zone, it is important that the CMS simulates their effects. The implementation of culverts in the CMS is based on equations developed by Bodhaine (1982). As a validation, the culverts are applied for the hydrodynamic calculations in a wetland application in Chesapeake Bay, Maryland.

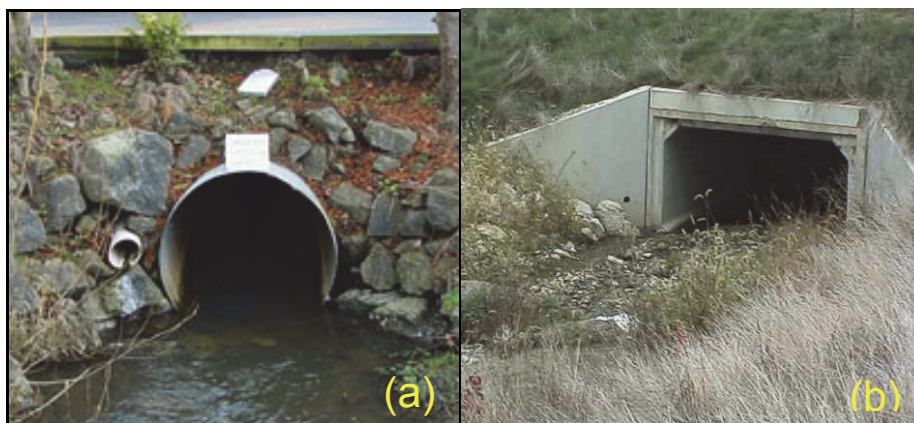


Figure 1. (a) Circular culvert, and (b) rectangular culvert.

COASTAL MODELING SYSTEM: The CMS, developed by the Coastal Inlets Research Program (CIRP), is an integrated suite of numerical models for simulating water surface elevation, current, waves, sediment transport, and morphology change in coastal and inlet applications. It consists of a hydrodynamic and sediment transport model, CMS-Flow, and a spectral wave model, CMS-Wave (Buttolph et al. 2006; Sanchez et al. 2011a; Sanchez et al. 2011b; Lin et al. 2008). Both are described in Part I of this series (Li et al. 2013).

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MATHEMATICAL FORMULATION: Based on the cross-sectional area, circular and rectangular culverts can be represented in the CMS (Figure 1). The flow through culverts is determined using the pipe or open channel flow equation. The CMS identifies the upstream and downstream cells occupied by the entrance and exit of each culvert and applies the same flow discharge as a source or sink term in the continuity equation. The specially designed implicit scheme for weirs and tide gates is modified for representing the culverts in the SIMPLEC algorithm (Wu 2012).

Bodhaine (1982) described six types of (unidirectional) flow conditions through a culvert that depends on the culvert slope and the upstream and downstream water levels. A sketch of the typical flow conditions for the culvert is shown in Figure 2. Considering the tidal flow in coastal zones, four types of flow conditions are grouped in the CMS and the equations described in the following can be applied for both circular and rectangular culverts.

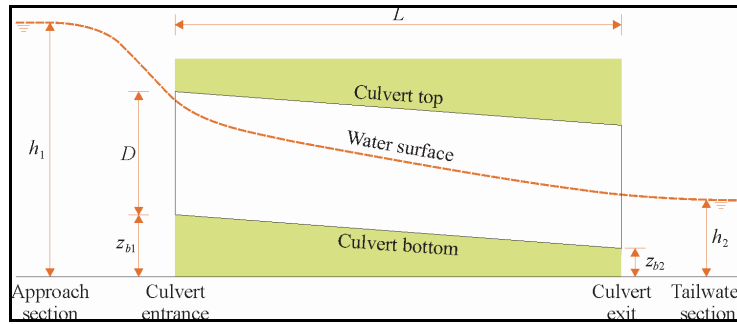


Figure 2. Sketch of culvert flow.

- (1) The headwater and tailwater are higher than the culvert top levels (height, D , plus invert elevations z_{b1}), i.e. the culvert inlet and outlet are submerged, and the culvert flow is an orifice flow determined by

$$Q = A \sqrt{\frac{2g(h_1 - h_2)}{K_L}} \quad (1)$$

where K_L is the coefficient of energy loss through the culvert, $K_L = K_i + K_f + K_o$, and K_i is the entrance loss coefficient, K_f is the friction loss coefficient, and K_o is the outlet loss coefficient. The friction loss (K_f) is determined by

$$K_f = \frac{fL}{4R_c} \quad (2)$$

where f is the Darcy-Weisbach friction coefficient, L is the culvert barrel length, and R_c is the hydraulic radius of the culvert barrel. Crowe et al. (2005) and Bodhaine (1982) presented the methods for the determination of f , K_i , and K_o .

- (2) The headwater (h_1) is greater than $1.5D + z_{b1}$ and tailwater (h_2) is lower than $D + z_{b2}$, and the culvert inlet is submerged but the exit is unsubmerged. In this case the culvert may be partly or fully occupied by flow (Bodhaine 1982). Here, for simplification, a fully occupied culvert is assumed and an orifice flow with free outflow is applied as

$$Q = A \sqrt{\frac{2g(h_1 - h_0)}{K'_L + 1.0}} \quad (3)$$

where $K'_L = K_i + K_f$, and h_0 is the tailwater and is assumed to be $D + z_{b2}$.

The headwater (h_1) is less than $1.5D + z_{b1}$ and the tailwater (h_2) is lower than $D + z_{b2}$, and both the culvert inlet and exit are unsubmerged. This is an open channel flow case, which can be critical or normal flow depending on the downstream water level and the culvert slope.

(3) For the critical flow case, the culvert discharge can be determined by

$$Q = A_c \sqrt{g \frac{A_c}{B_c}} \quad (4)$$

where A_c and B_c are the area and the top width of the flow at the culvert opening, respectively, both being function of the flow depth (h_c) at the opening.

(4) For the normal flow case, the culvert discharge is determined by

$$Q = \frac{1}{n} A_c R_c^{2/3} S_c^{1/2} \quad (5)$$

where S_c is the hydraulic gradient. Considering the local head loss, Equation (5) can be extended to the following form:

$$Q = A_c \sqrt{\frac{2g(h_1 - h_2)}{K'_i + K'_o + 2gn^2L / R_c^{4/3}}} \quad (6)$$

where K'_i and K'_o are the local head loss coefficients at the culvert entrance and exit, respectively. In this flow case, the local head loss coefficients are assumed to be the same as K_i and K_o in Equation (1).

NUMERICAL IMPLEMENTATION: Figure 3 shows a sketch of a culvert setup in the CMS. The culverts can cross multiple land cells. The implementation requires the specifications of the following parameters: upstream and downstream cells, the culvert invert elevation (relative to the model datum), the culvert type (circular or rectangular) and associated scales, the length of the culvert, the local head loss coefficients, the friction coefficients, the outflow directions at the entrance and exit ends, and a flap gate.

For a circular culvert, the diameter is specified, and for a rectangular, the width and height are specified. The local head loss coefficients at the bay and sea sides may vary with tidal current direction. For the culvert with a flap gate, the flow is unidirectional from the upstream to the downstream. Thus, the identification of the upstream and downstream cells becomes more important for this case.

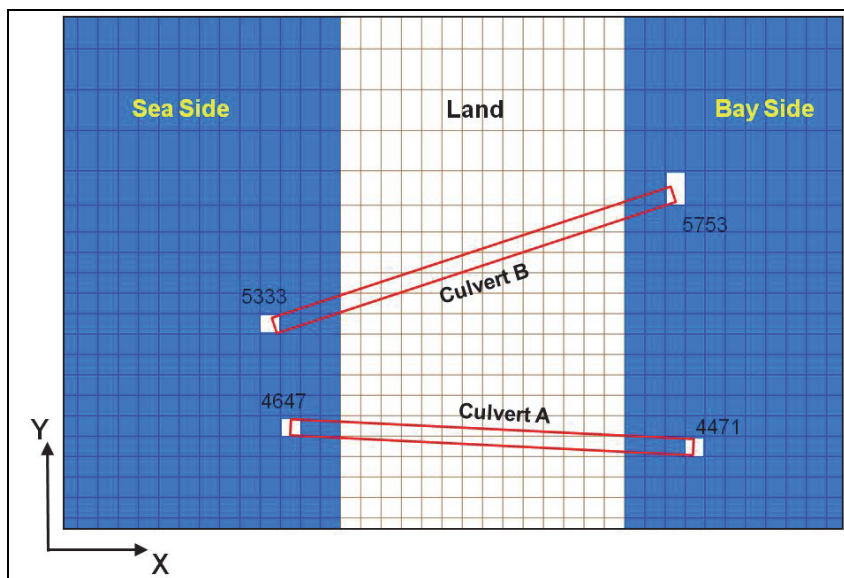


Figure 3. Setup of culvert in the CMS.

The mass flux through culverts is treated as a sink or source in the continuity equation at the culvert entrance and exit cells, respectively. There are two ways to treat the momentum flux through culverts. The first method is to add the momentum flux as source to the momentum equations at the culvert entrance and exit cells, like the mass flux. For this method, the outflow directions at both cells for tide current need to be specified. The second method is to assume that the momentum flux is small and can be neglected in the momentum balance calculations. For a direct discharge of culvert flow into bayside or seaside, the first method may be a better selection. If an energy dissipater or stilling basin exists at the culvert outlet, the second method may apply. A specification of the outflow direction between 0° and 360° corresponds to the first method and a direction less than 0° or larger than 360° implicates the second selection.

In order to enhance the numerical stability, the culvert flow Equations (1), (3), (4), or (6) are expanded to a first-order Taylor series, and an implicit method is developed by inserting this Taylor series into the water level correction (Wu 2012).

INPUT SPECIFICATIONS: Multiple culverts can be specified by identifying the paired entrance and exit cell IDs (the cell counter on the flow grid) in the CMS. An advanced card is designed, starting with “CULVERT_BEGIN” and ending with “CULVERT_END”. A description of the culvert parameters is shown in Table 1.

In a demonstration case, consider the simulation with two culverts as shown in Figure 3; A and B. Culvert A consists of two cells with ID numbers, 4471 on the bay side and 4647 on the sea side, and a length of 480 m. Culvert B has two cells with ID numbers 5753 on the bay side and 5333 on the sea side, and a length of 530 m. In this case, number culvert = 2. The advanced card is given in Figure 4 with red marked for culvert A and blue for culvert B.

In the above specifications, culvert A has a rectangular and culvert B a circular cross section. The outflow direction of culvert A on the bay side is 355° and 175° on the sea side. For culvert B, the outflow direction is 20° and 200° , respectively, on the bay and sea sides.

Table 1. Specifications of culvert parameters in the CMS.		
Input	Format	Note
Number of Culvert	[card=NUMBER_CULVERTS] [name=numculvert, type=integer]	Number of culvert structures
Cell ID	[card=CELLS] [name=idculvert, type=integer]	A pair of cell IDs for each culvert. The first one is the cell ID on the bay side of the culvert and the second one on the sea side
Type of Culvert	[card=TYPE] [name=CulvertType, type=char]	Type of culvert CIR: circular culvert BOX: rectangular culvert
Culvert with Flap Gate	[card=FLAP_GATE] [name=CulvertFlap, type=char]	Flap gate OFF: without gate ON: with flap gate
Radius of Culvert	[card=RADIUS] [name=Radius, type=float]	Radius of circular culvert
Width of Culvert	[card=WIDTH] [name=Width, type=float]	Width of rectangular culvert
Height of Culvert	[card=HEIGHT] [name=Height, type=float]	Height of rectangular culvert
Length of Culvert	[card=LENGTH] [name=Length, type=float]	Length of culvert barrel
Darcy Friction Factor	[card=DARCY_FRICTION_FACTOR] [name=CulvertFric, type=float]	Darcy-Weisbach friction coefficient for the culvert fully occupied by flow
Manning (n)	[card=MANNING_COEFFICIENT] [name=CulvertMann, type=float]	Manning friction coefficient for the culvert partly occupied by flow
Invert Elevation of Culvert	[card=INVERT_ELEVATION] [name=CulvertElevBay/CulvertElevSea, type=float]	A pair of invert elevations on the bay side and the sea side of culvert
Entry Head Loss	[card=ENTRY_HEAD_LOSSES] [name=CulvertHeadLossEntry, type=float]	A pair of local flow entrance head loss at the bay side and the sea side
Exit Head Loss	[card=EXIT_HEAD_LOSSES] [name=CulvertHeadLossExit, type=float]	A pair of local flow exit head loss at the bay side and the sea side
Outflow Angle	[card=OUTFLOW_ANGLES] [name=AngleCulvertBay/AngleCulvertSea, type=float]	A pair of outflow directions of culvert on the bay side and the sea side (counter-clockwise from positive x-axis)

CULVERT STRUCTURES AT POPLAR ISLAND, MD: Poplar Island is located in Chesapeake Bay, MD, to the south of the Baltimore Harbor (Figure 5). The island had a size of more than 1000 acres in the mid-1800's but, it has been shrinking since then due to continuous shoreline erosion. The island restoration project started in the 1990s, which used dredged materials from the Chesapeake Bay navigation channels to rebuild the island.

As shown in Figure 5, Poplar Island has been constructed into a number of wetland cells. Separated numerical models were built to evaluate circulation for individual cells. This example of the culvert implementation in the CMS focuses on Cell-3D because a number of culverts were built for water exchange between the cell and the bay.

Figure 6 shows the locations of four culverts for the Cell-3D in the CMS domain and Figure 7 the culvert specifications in a SMS/CMS advanced card. As shown in Figure 7, the parameters for the 4 culverts are shaded by different colors. A full list of the parameters is displayed for the first culvert and only different parameters are for the other culverts, such as the culvert cell IDs and the lengths of culvert barrel.

CMS-FLOW Model Control

Flow | Sediment | Salinity | Tidal | Wind/Wave | Output | Cells | Input | Advanced

Advanced Cards

CULVERT_BEGIN	
NUMBER_CULVERTS 2	
CELLS	4471 4647 5753 5333
TYPE	BOX CIR
FLAP_GATE	OFF OFF
RADIUS	2.0 2.0
WIDTH	5.0 5.0
HEIGHT	2.0 2.0
LENGTH	480 530
DARCY_FRICTION_FACTOR	0.04 0.04
MANNINGS_COEFFICIENT	0.02 0.02
INVERT_ELEVATIONS	-2.0 -2.0 -2.0 -2.0
ENTRY_HEAD_LOSSES	0.5 0.5 0.5 0.5
EXIT_HEAD_LOSSES	1.0 1.0 1.0 1.0
OUTFLOW_ANGLES	355.0 175.0 20.0 200.0
CULVERT_END	

Figure 4. Culvert Specifications in the SMS/CMS.

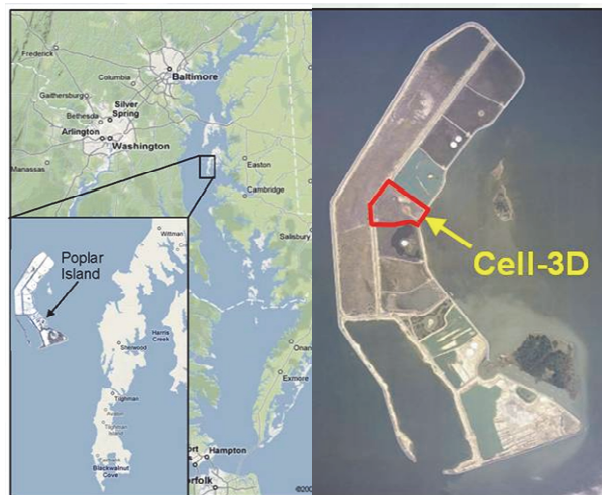


Figure 5. Poplar Island, MD and constructed wetland cells.

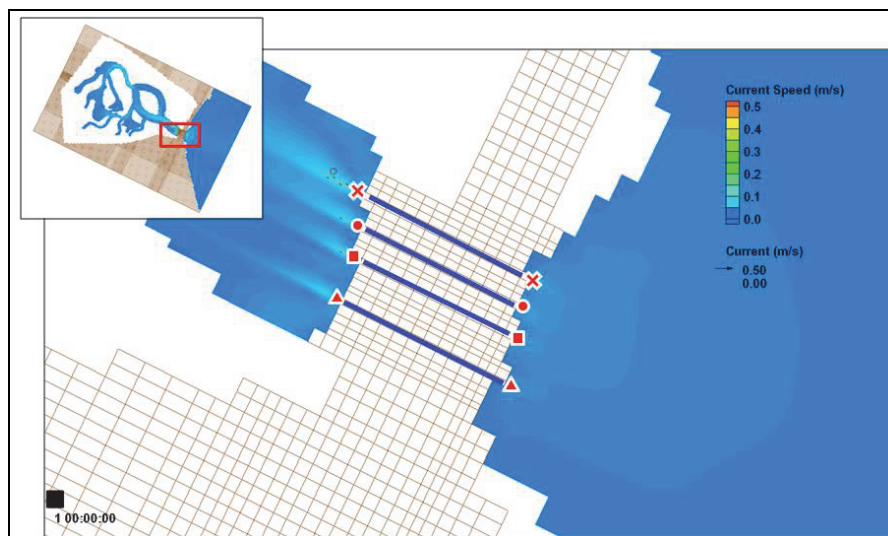


Figure 6. Four Culverts in the CMS domain.

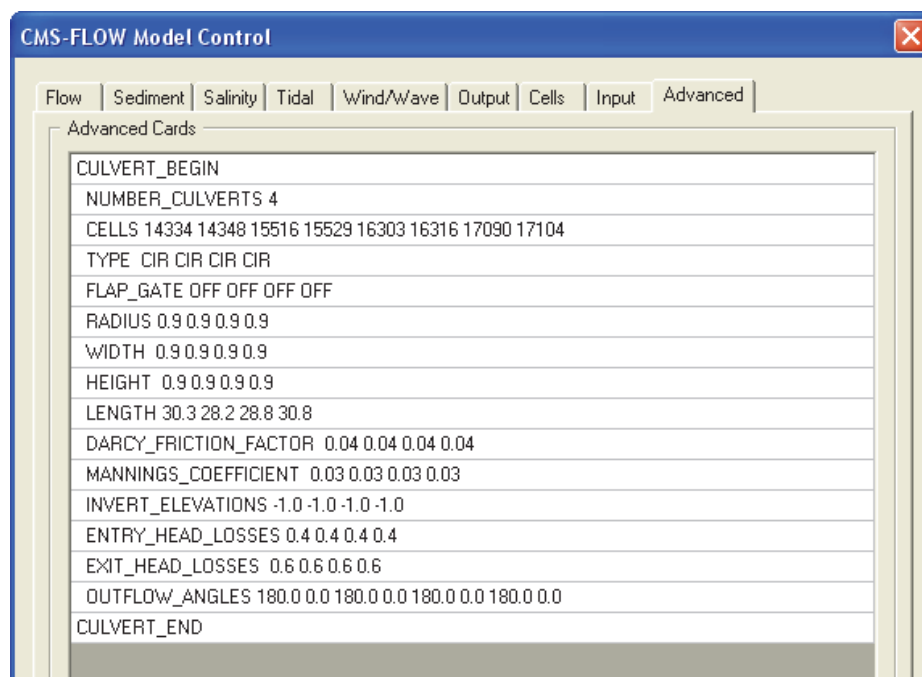


Figure 7. Culvert Specifications in a SMS/CMS advanced card.

DISCUSSION: A previous numerical modeling study of Cell-3D (Sanchez and Brown, personal communication, June 9, 2008) showed general hydrodynamic features around the wetland cell. The original CMS setup did not have the implementation of culvert structures. In this application the same CMS model was adopted, culvert structures configured in the system, and a 50-day simulation was conducted.

The calculated circulation pattern is similar to the distribution of current magnitudes by the previous simulation, and strong currents occur near the tidal inlet. Figure 8 is a snapshot of the current field from the CMS simulation during an ebb and flood tide. The implementation of

culverts induces the current speeds of 20-30 cm/s at the entrances and exits of the culverts on the wetland cell side and sea side.

The field data were collected inside the wetland cell. Figures 9 and 10 show the locations of four survey stations and the comparisons between the calculated and measured water levels and currents. A Principle Component Analysis was performed to obtain the flood and ebb directions. Station 1 is located near a culvert and shows strong flood dominance with a peak current speed up to 20 cm/s. Current speeds are significantly reduced as tidal water reaches inside the wetland cell, indicating weak flushing at those locations. The hydrodynamic features are well reproduced by the model with the introduction of the culvert structures.

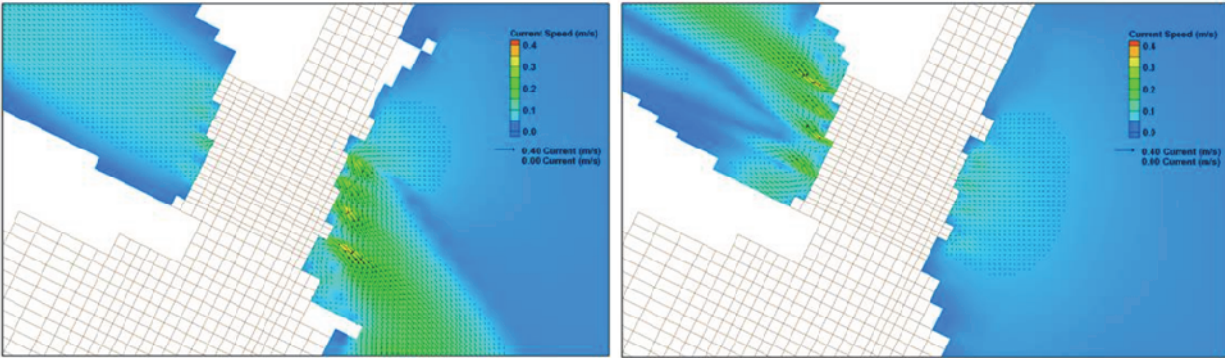


Figure 8. Snapshot of the Current Field during an Ebb and Flood Tide.

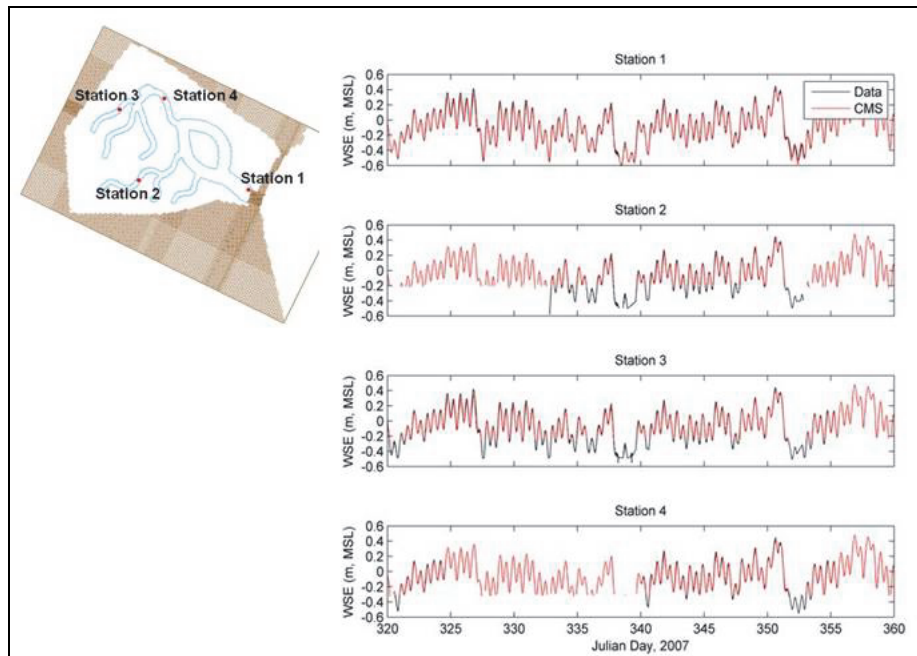


Figure 9. Water Levels at the Four Survey Stations.

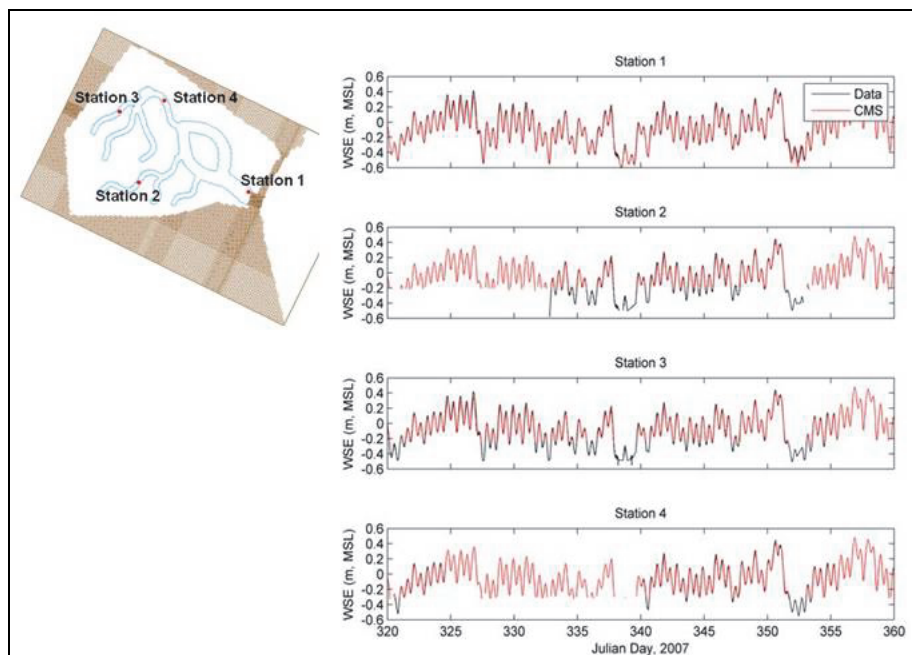


Figure 10. Currents at the Four Survey Stations. Positive indicates the flood and negative the ebb directions.

SUMMARY: Culvert structures were incorporated into the CMS and the implementation procedure was described in this note. The application of the algorithms in the CMS was demonstrated and hydrodynamic results were validated via the comparisons with the measurements and the calculated results from a previous CMS study.

ADDITIONAL INFORMATION: This CHETN was prepared as part of the CIRP and was written by Dr. Honghai Li (Honghai.Li@usace.army.mil, voice: 601-634-2840, fax: 601-634-3080), Alejandro Sanchez of the US Army Engineer Research and Development Center (ERDC), Coastal and Hydraulics Laboratory (CHL), Dr. Weiming Wu of University of Mississippi, and Dr. Christopher W. Reed of URS. The CIRP Program Manager, Dr. Julie D. Rosati (Julie.D.Rosati@usace.army.mil), the assistant Program Manager, Dr. Zeki Demirebilek, and the Chief of the Coastal Engineering Branch at CHL, Dr. Jeffrey P. Waters, reviewed this CHETN. Files for the study may be obtained by contacting the author. This CHETN should be cited as follows:

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REFERENCES

Bodhaine, G.L. 1982. *Measurement of peak discharge at culverts by indirect methods*, *Techniques of Water Resources Investigations of the United States Geological Survey*, Book 3, Chapter A3, US Geological Survey, Washington.

- Buttolph, A. M., C. W. Reed, N. C. Kraus, N. Ono, M. Larson, B. Camenen, H. Hanson, T. Wamsley, and A. K. Zundel. 2006. *Two-dimensional depth-averaged circulation model CMS-M2D: Version 3.0, Report 2, sediment transport and morphology change*. Coastal and Hydraulics Laboratory Technical Report ERDC/CHL-TR-06-7. Vicksburg, MS: US Army Engineer Research and Development Center.
- Crowe, C.T., D. F. Elger, and J. A. Roberson. 2005. *Engineering Fluid Mechanics*, Jon Wiley & Sons, Inc.
- Li, H., A. Sanchez, W. Wu, and C. W. Reed, 2013. *Implementation of structures in the CMS: Part I, Rubble Mound*. Coastal and Hydraulics Engineering Technical Note ERDC/CHL CHETN-IV-93. Vicksburg, MS: US Army Engineer Research and Development Center.
- Lin, L., Z. Demirbilek, and H. Mase. 2011. Recent capabilities of CMS-Wave: A coastal wave model for inlets and navigation projects. *Journal of Coastal Research*, Special Issue, 59, 7-14.
- Lin, L., Z. Demirbilek, H. Mase, J. Zheng, and F. Yamada. 2008. *CMS-Wave: A nearshore spectral wave processes model for coastal inlets and navigation projects*. Coastal and Hydraulics Laboratory Technical Report ERDC/CHL-TR-08-13. Vicksburg, MS: US Army Engineer Research and Development Center.
- Sanchez, A., W. Wu, T. M. Beck, H. Li, J. Rosati III, R. Thomas, J. D. Rosati, Z. Demirbilek, M. Brown, and C. W. Reed. 2011a. *Verification and validation of the Coastal Modeling System, Report 3: Hydrodynamics*. Coastal and Hydraulics Laboratory Technical Report ERDC/CHL-TR-11-10. Vicksburg, MS: US Army Engineer Research and Development Center.
- Sanchez, A., W. Wu, T. M. Beck, H. Li, J. D. Rosati, Z. Demirbilek, and M. Brown. 2011b. *Verification and validation of the Coastal Modeling System, Report 4: Sediment transport and morphology change*. Coastal and Hydraulics Laboratory Technical Report ERDC/CHL-TR-11-10. Vicksburg, MS: US Army Engineer Research and Development Center.
- Wu, W. 2012. *Implementation of structures in the implicit CMS2D model*. An Interim Report to Coastal Inlets Research Program, ERDC, USACE.

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